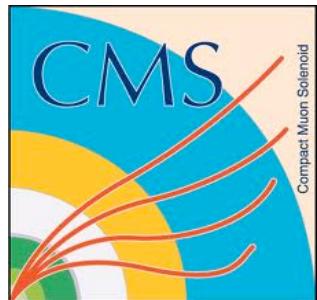
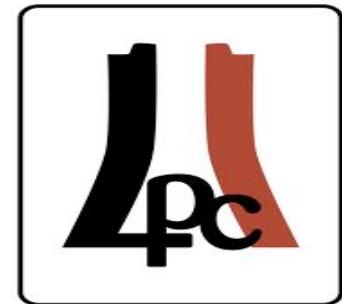


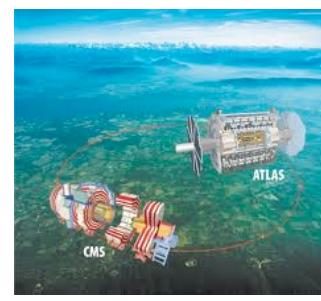
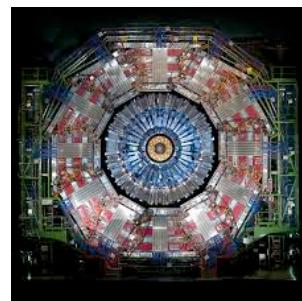
Observation of a Structure in the J/ψφ Mass Spectrum at CMS



Kai Yi (University of Iowa)
for the CMS Collaboration



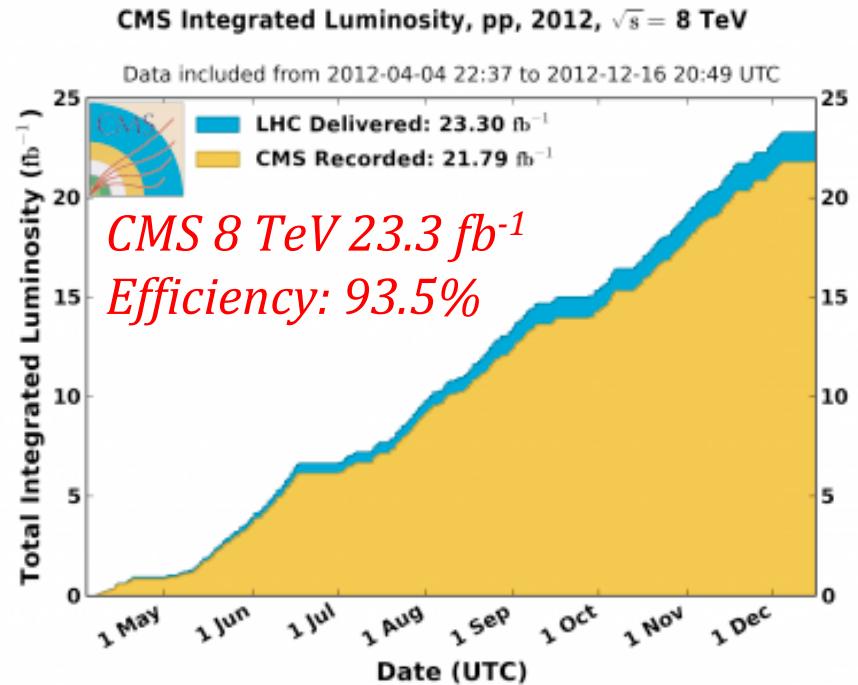
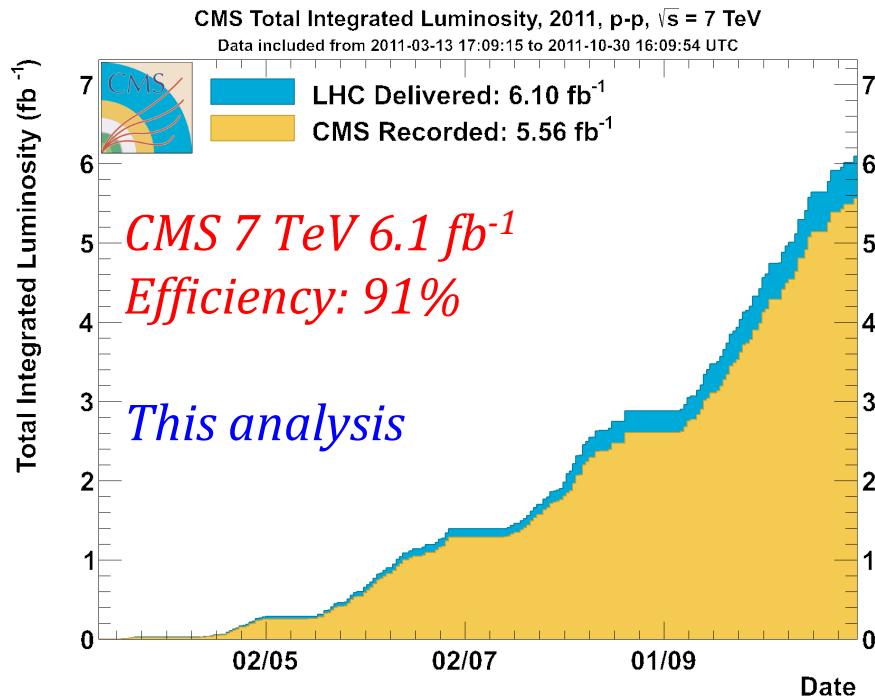
Joint Experimental-Theoretical Physics Seminar
Fermilab, Oct 18, 2013



Outline

- Introduction (D0 talk)
- CMS detector and trigger
- Observation of $Y(4140)$ @CMS and evidence for an additional structure
- Summary (D0+CMS)

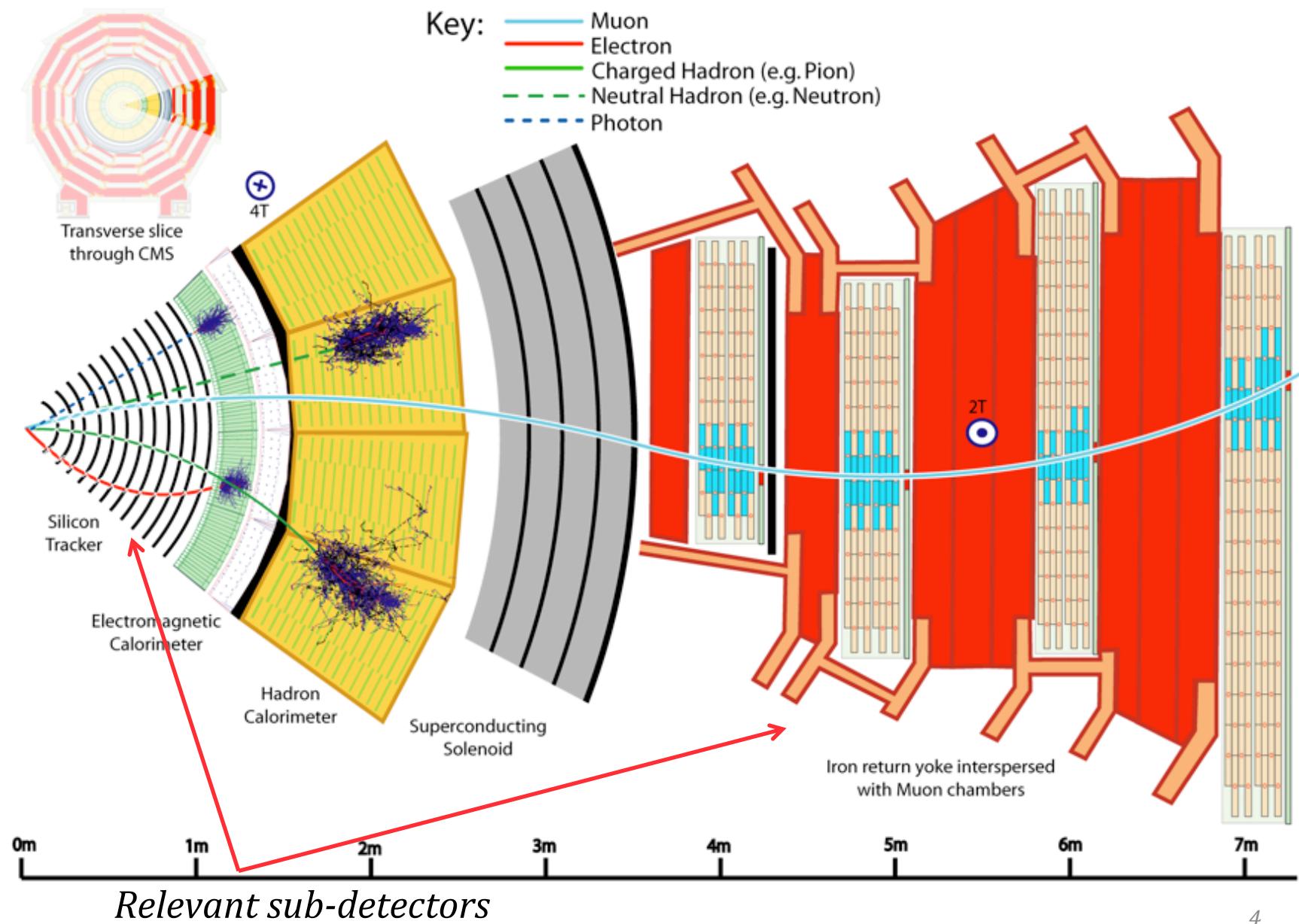
CMS & LHC



CMS collects data very efficiently

- CMS Yields large amounts of data at the world's **Highest Energy**
 - CMS/ATLAS just discovered the Higgs, confirms & completes the SM
 - Enormous opportunities to search for new phenomena

The CMS Detector



CMS Detector Performance

Excellent muon/silicon detectors for quarkonium:

- Muon system
 - High-purity muon identification
 - Good dimuon mass resolution ($\Delta m / m \sim 0.6\%$ for J/ψ)
- Silicon Tracking detector
 - excellent track momentum resolution ($\Delta p_T / p_T \sim 1\%$)
 - excellent vertex reconstruction
- Observation of $B_s(\mu^+\mu^-)$ ($>4\sigma$) shows an excellent combined performance of the all-silicon tracker and muon detector
 - identifying and measuring muons with high resolution
 - strong background rejection capabilities.

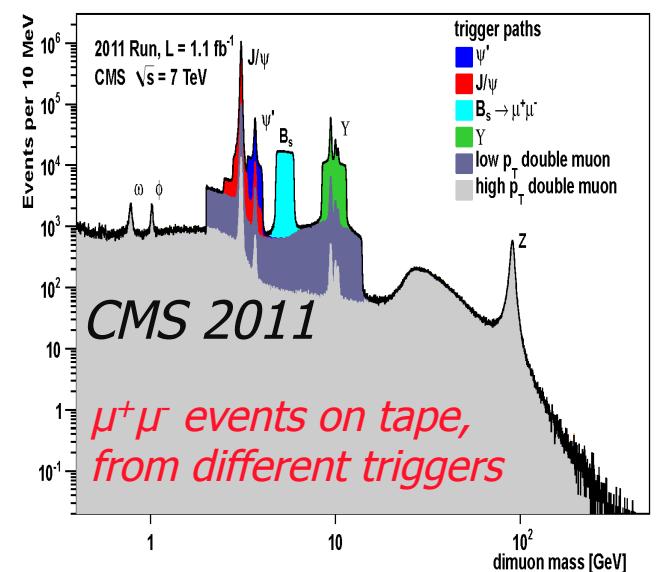
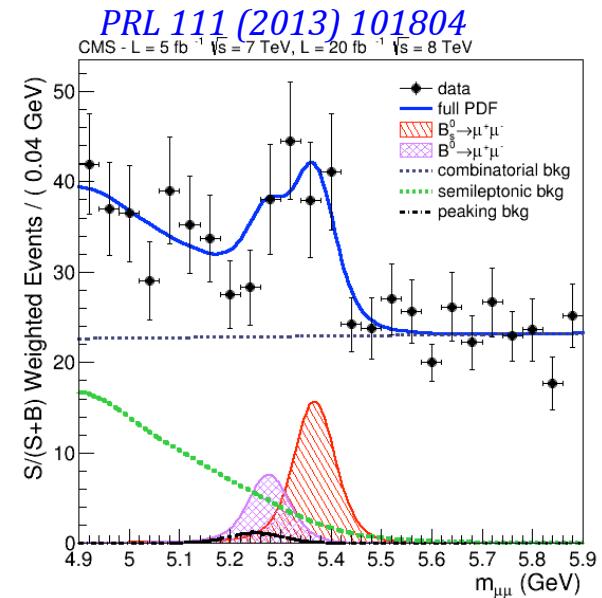
LHC luminosity and CMS trigger:

- Collect data at increasing instantaneous luminosity
- Triggers are essential ingredients
 - Special trigger for different analysis

For this analysis:

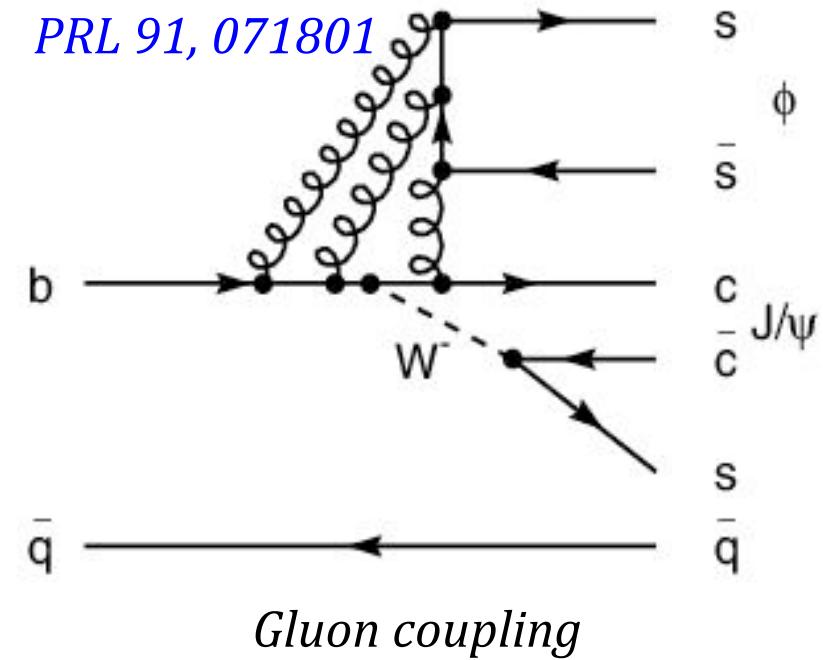
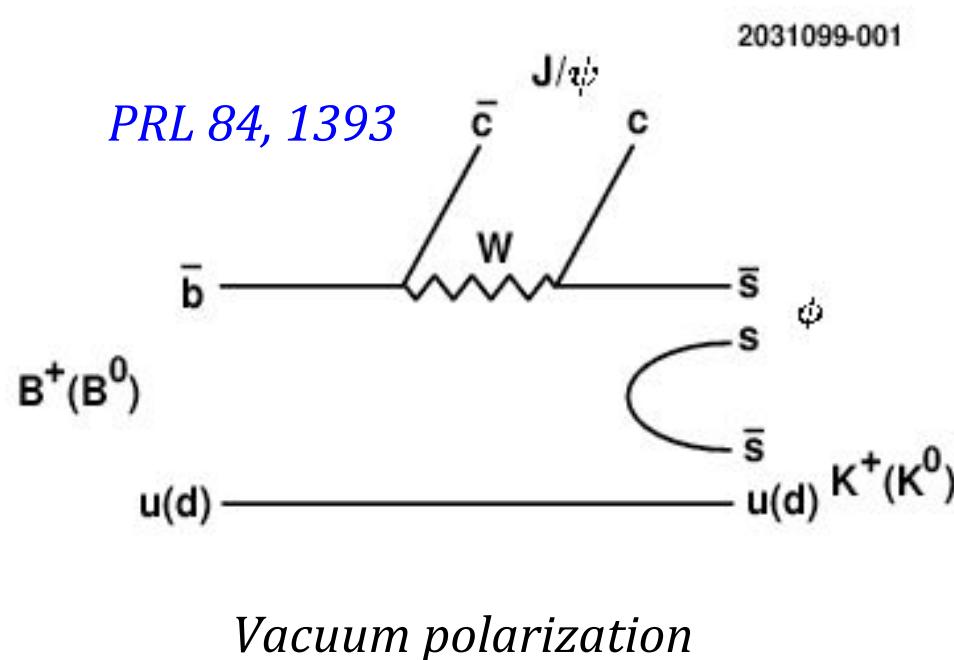
displaced dimuon vertex &

minimum (di)muon transverse momentum



Search Structures $\rightarrow J/\psi \phi$ via B Decays

- Experimentally attractive to search through clean $B \rightarrow J/\psi \phi K^+$ channel
 - taking advantage of B lifetime and narrow B mass window
 - $B \rightarrow J/\psi \phi K$ is OZI suppressed, so low rate from phase space decays
 - constrained phase space favors forming of two-body structures



Analysis strategy

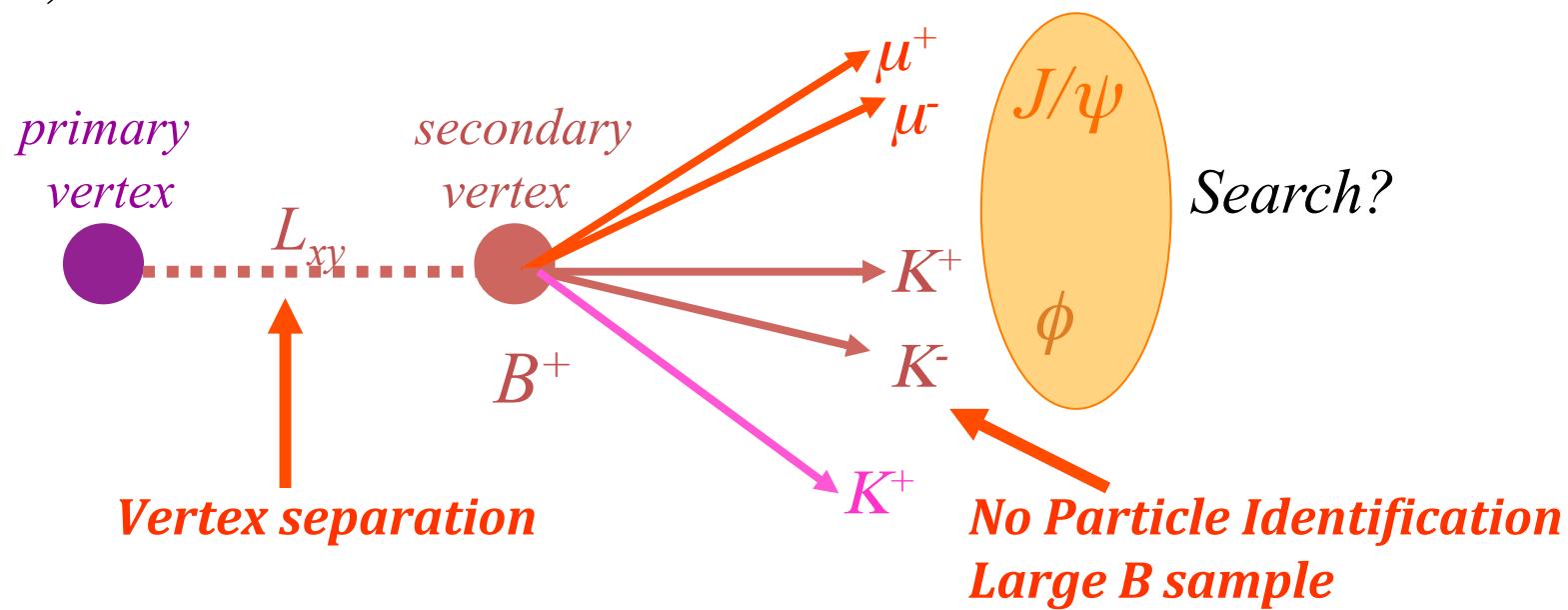
- I) Reconstruct B^+ (charge conjugation implied) as:

$$B^+ \rightarrow J/\psi \phi K^+$$

$$J/\psi \rightarrow \mu^+ \mu^-$$

$$\phi \rightarrow K^+ K^-$$

- II) Search for structure in $J/\psi \phi$ mass spectrum inside B^+ mass window



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026>

CMS: BPH-11-026, [arXiv:1309.6920 \[hep-ex\]](https://arxiv.org/abs/1309.6920), submitted to PLB

Event Selections

-- $|\eta|$ for all tracks ≤ 2.4

--*probability(χ^2) for J/ψ vertex fit > 10%, probability(χ^2) for B^+ vertex fit > 1%*

-- p_T (kaon track) $> 1 \text{ GeV}$

-- *J/ψ vertex flight length significance ≥ 3*

Divided dataset into A & B due to different trigger requirements

Dataset A: $p_T(J/\psi) > 7 \text{ GeV}$

Dataset B: $p_T(J/\psi) > 7 \text{ GeV} \text{ & } p_T(\mu^+/\mu^-) > 4 \text{ GeV}$

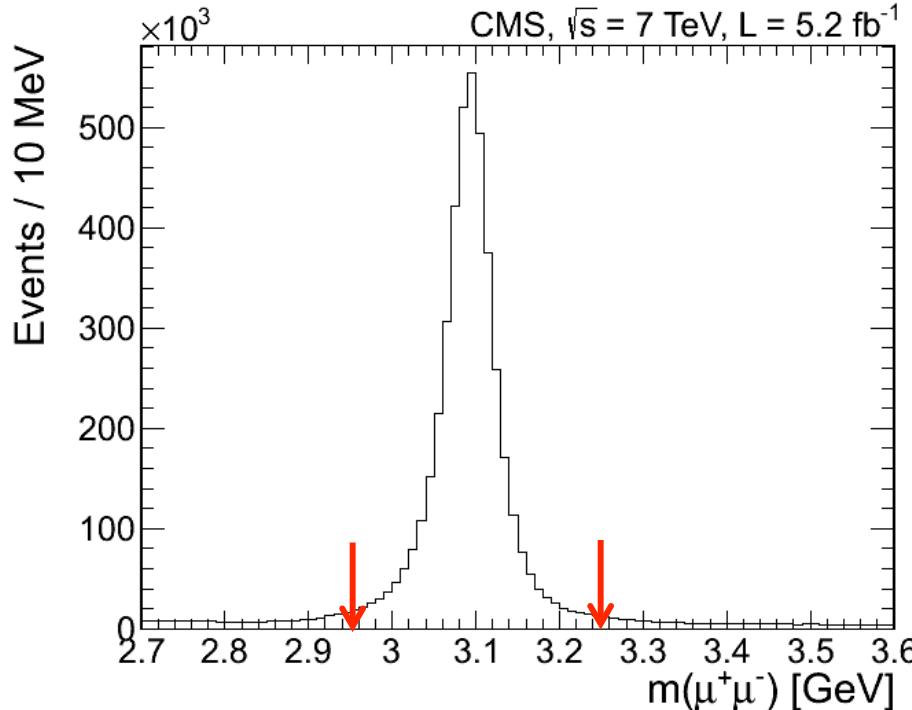
--mass window:

$J/\psi (\pm 150 \text{ MeV})$ and ϕ in $[1.008, 1.035] \text{ GeV}$ (Breit-Wigner shape)

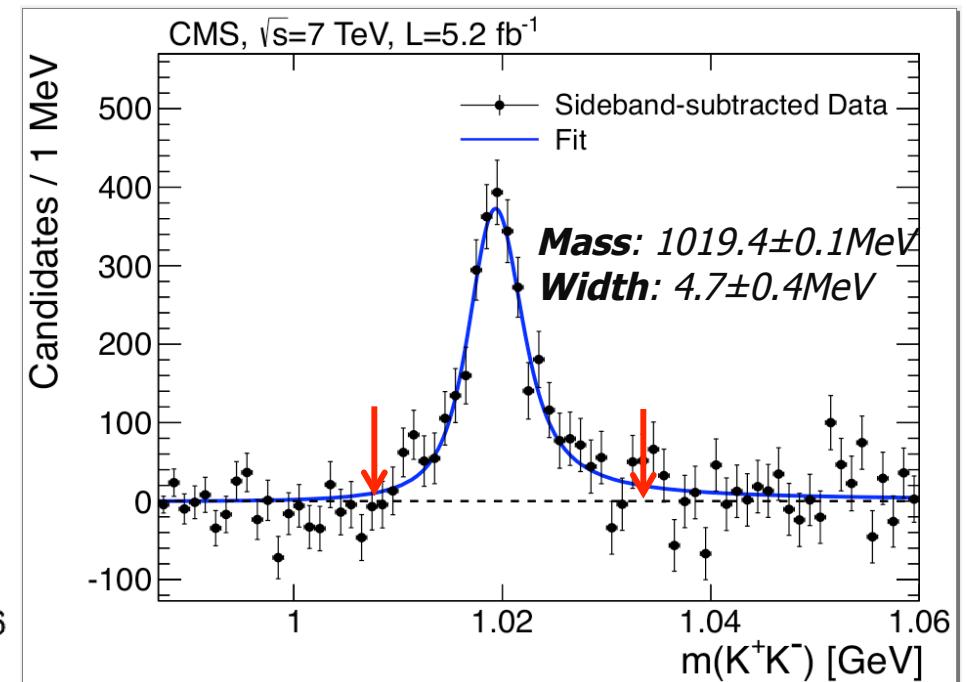
constraint $\mu^+\mu^-$ to J/ψ PDG mass value

J/ Ψ and ϕ Signal

$m(\mu^+\mu^-)$ before forming the B signal
Non-prompt from displaced trigger



The B^+ sideband subtracted $m(K^+K^-)$
where $m(J/\psi\phi K^+)$ is within $\pm 3\sigma$ of $m(B^+)$



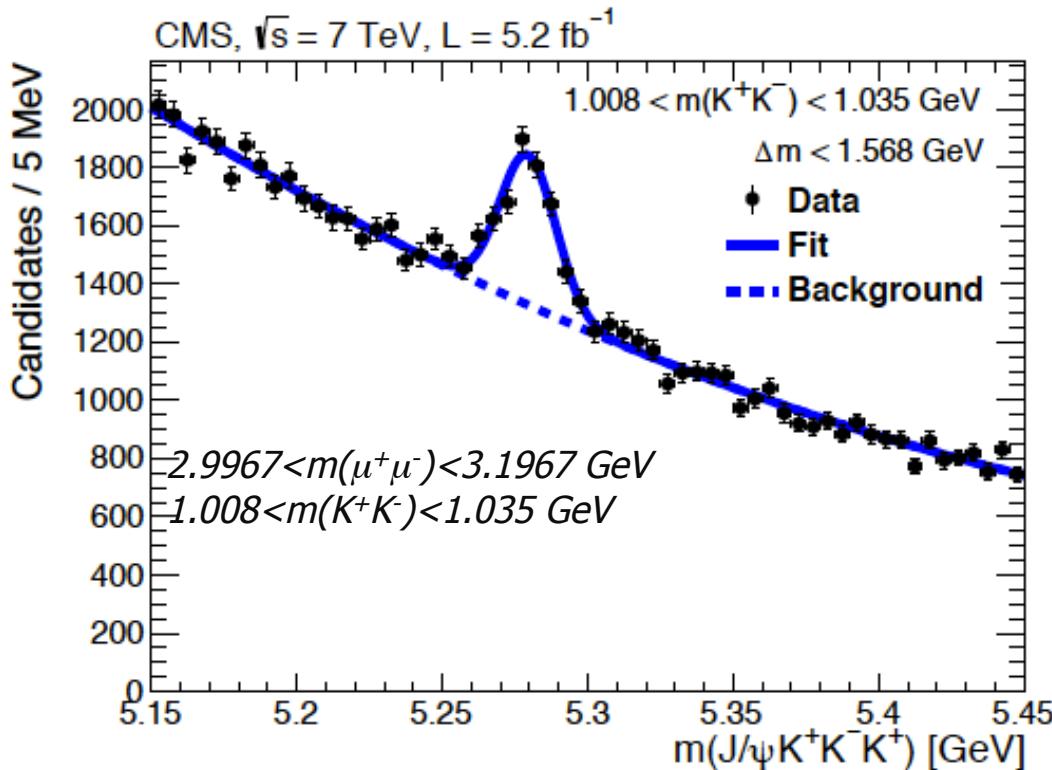
Resolution consistent with predicted expectation

- A clear and clean J/ Ψ signal
- Nice ϕ line-shape, consistent with PDG parameters
- $B \rightarrow J/\psi\phi K^+$ dominates after ϕ mass restriction

Displaced triggered

The B Signal

$B^+ \rightarrow J/\psi \phi K^+$ decay



Signal PDF: Gaussian
~2500 B^+

Background PDF:
2nd-order Chebyshev polynomial

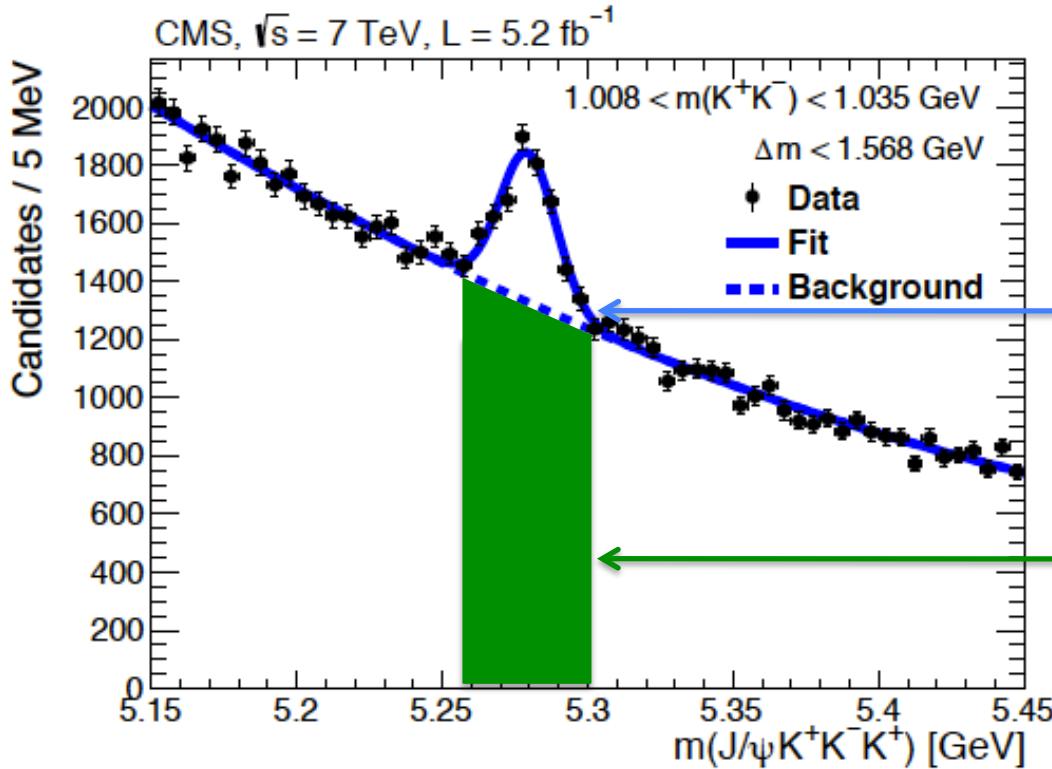
Mass: consistent with PDG value
($5.2796 \pm 0.0006 \text{ GeV}$)

Width: consistent with simulation
($9.6 \pm 0.7 \text{ MeV}$)

Remove B_s^0 contamination requiring $\Delta m > 1.568 \text{ GeV}$

Largest $B^+ \rightarrow J/\psi \phi K^+$ sample collected in the world up to date
~20 times of CDF statistics (115 ± 12); ~7 of LHCb statistics (346 ± 20)

Various Components



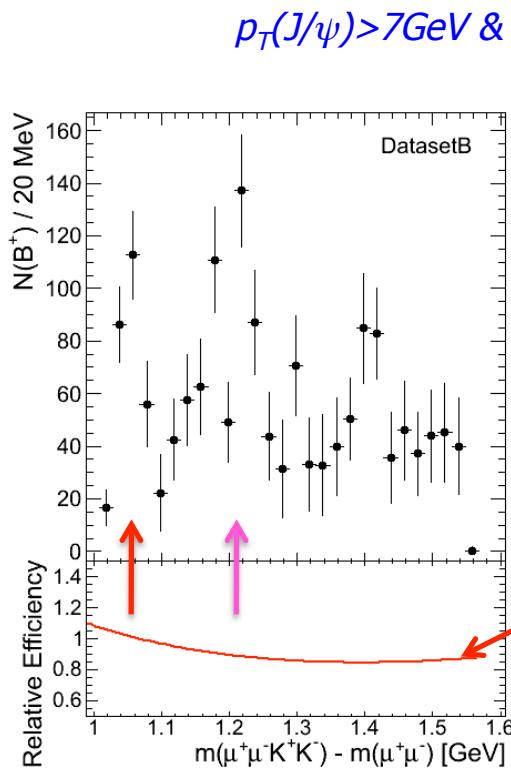
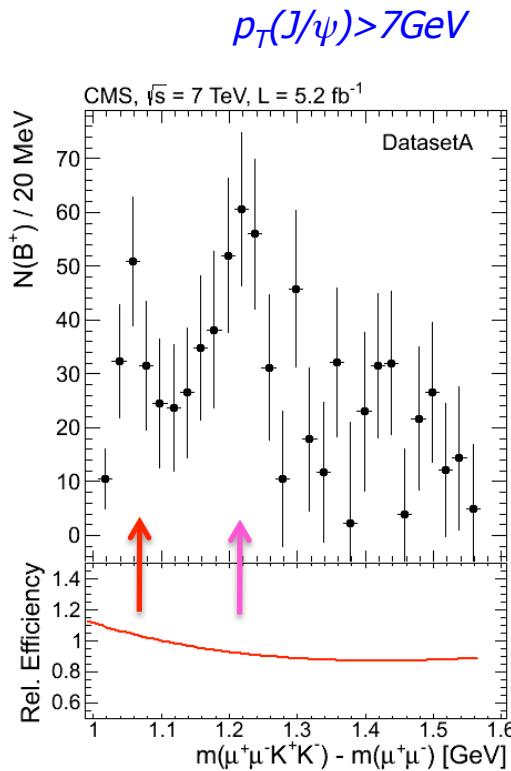
Possible components for $B^+ \rightarrow J/\psi \phi K^+$ final state (ignoring interference):

1. Phase space events: 3-body decay: $B^+ \rightarrow J/\psi \phi K^+$
2. Possible peaks in $m(J/\psi \phi)$: $B^+ \rightarrow X K^+, X \rightarrow J/\psi \phi \rightarrow J/\psi \phi K^+$
3. Possible peaks in $m(J/\psi K^+)$: $B^+ \rightarrow X \phi, X \rightarrow J/\psi K^+ \rightarrow J/\psi \phi K^+$
4. Possible peaks in $m(\phi K^+)$: $B^+ \rightarrow X J/\psi, X \rightarrow \phi K^+ \rightarrow J/\psi \phi K^+$

J/ψφ Invariant Mass Spectrum

- The mass difference $\Delta m = m(\mu^+ \mu^- K^+ K^-) - m(\mu^+ \mu^-)$ is used

- Extracting the Δm spectrum
 - Divide the dataset into the 20 MeV Δm bins
 - Extract the number of B events for each Δm by fitting the $J/\psi\phi K$ spectrum
 - Plot the B yield as a function of Δm



◆ Means fixed to the PDG B mass
◆ RMS fixed to the signal MC values

*correct the spectrum
by efficiency before fitting*

*Relative efficiency over Δm :
approx. flat*

Reflection in Three-body Decays

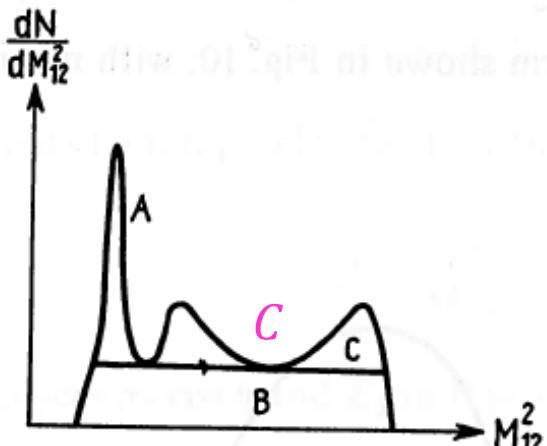
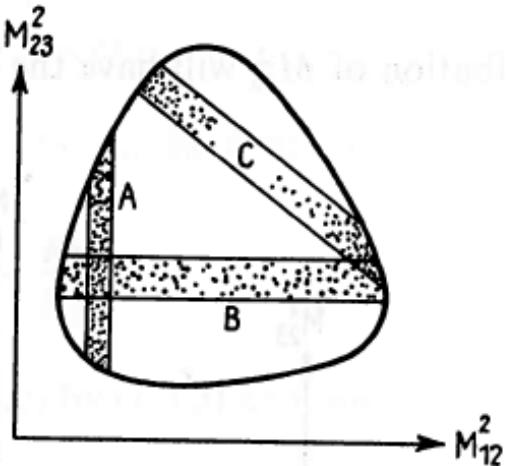


Fig. 11



Three resonances:

$$A \rightarrow M_{12}$$

$$B \rightarrow M_{23}$$

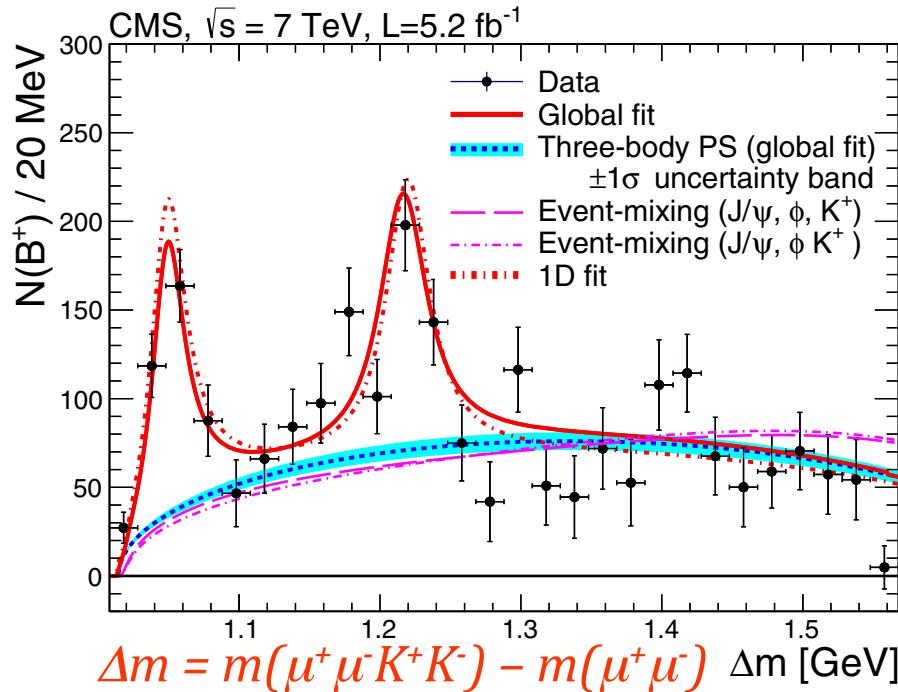
$$C \rightarrow M_{13}$$

Examples: ρ^+ , N^{*++} , N^{*+} in
 $\pi^+ + p \rightarrow \pi^+ + \pi^0 + p$

Depending on J^{PC} , B&C can be structure-less or structures in M_{12} . In this example, B shows flat distribution in M_{12} and C shows two structures in M_{12} .

CMS investigated it carefully, more details in backup

Background Shape Studies



Event mixing to study the Δm shape

-- $J/\psi, \phi, K^+$ from different event

-- ϕ, K^+ from the same event, J/ψ from different event. This is to get the impact on Δm from possible ϕK^+ resonances

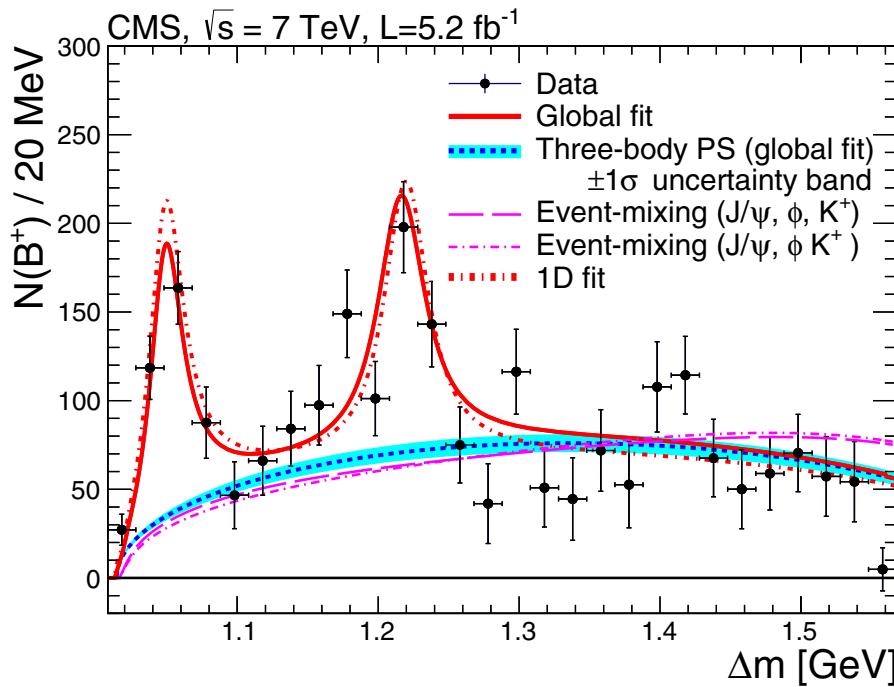
Require the $J/\psi \phi K^+$ mass around B mass

Event-mixing Δm shapes are slightly distorted compared to three-body phase space

--the possible effect is on high Δm region

--the three-body phase space shape is more conservative at low Δm region where the two structures are observed.

The Fit Result assuming Two Peaks



1D fit:

Binned χ^2 fit to the extracted Δm spectrum using the same BW and PS shape.

BW: Relativistic Breit-Wigner convoluted with mass resolution

1D result agrees with global fit result

Global fit—2 dimensional fit

(simultaneous fit of $m(B)$ and Δm with implicit background subtraction)

	$\Delta m \text{ (MeV)}$	$\Gamma \text{ (MeV)}$	Signal Yield
Peak 1	1051.3 ± 2.4	28_{-11}^{+15}	310 ± 70
Peak 2	1217.1 ± 5.3	38_{-15}^{+30}	418 ± 170

Significance: $>5\sigma$ (1st peak); $>3\sigma$ (2nd peak)

Significance

To evaluate the significance, three fits are performed

- 1) a background-only fit (null-hypothesis);
- 2) a background plus a single S-wave relativistic BW signal function for peak 1
- 3) a background plus two S-wave relativistic BW functions for peak 1 & 2

The log-likelihood ratio $-2\Delta\ln L$ (global fit) or the χ^2 change $\Delta\chi^2$ (binned χ^2 fit) are:

	Δm (MeV)	Γ (MeV)	Signal Yield	$-2\Delta\ln L/\Delta d.o.f$	$\Delta\chi^2/\Delta d.o.f$
Peak 1	1051.3 ± 2.4	28_{-11}^{+15}	310 ± 70	$58/3$	$53/3$
Peak 2	1217.1 ± 5.3	38_{-15}^{+30}	418 ± 170	$36/3$	$37/3$

The p-values are very low for both peaks ($< 2.9 \times 10^{-7}$) based on above number;

We performed pseudo-experiments to estimate the significance of peak 1

Significance

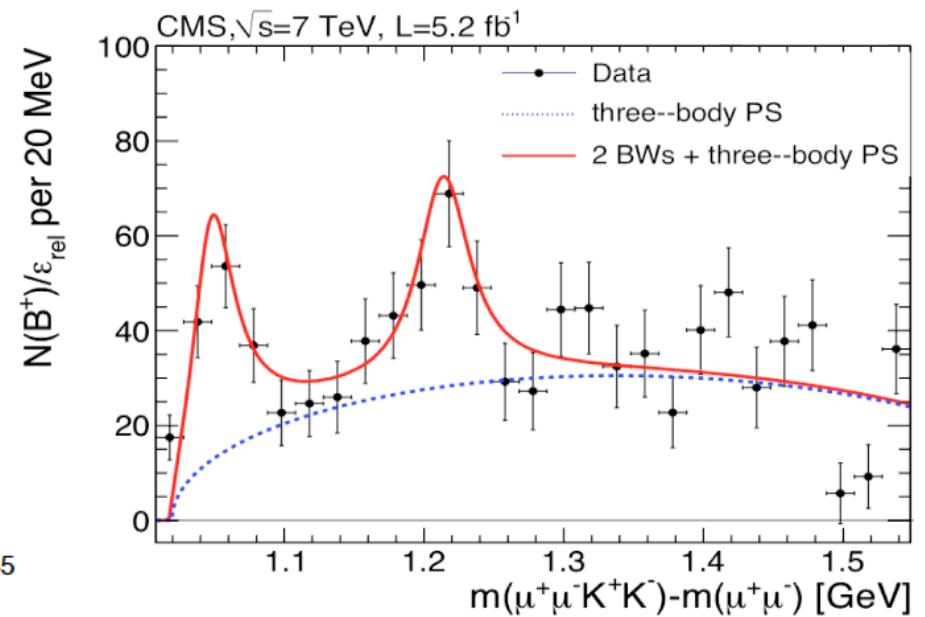
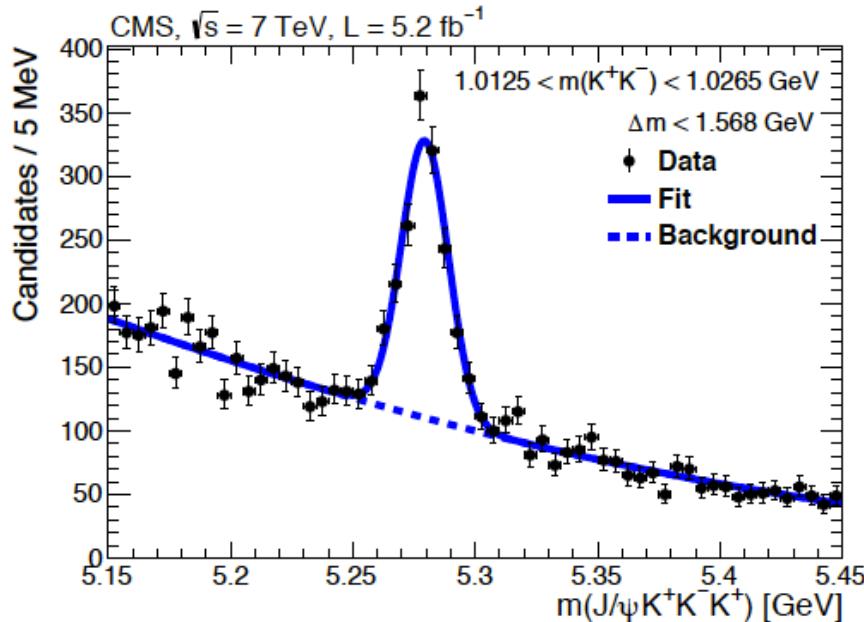
- We determine significance of peak 1 from simulation (Toy MC):
 - Using *Three-body decay Phase Space* only to generate the Δm spectrum
 - Find the most significant fluctuation for each trial anywhere in Δm with ± 3 times of the uncertainty around CDF value width between **10 MeV** (half bin width) and **80 MeV**
 - Count it if $\Delta\chi^2 \geq 53$ ($\Delta\chi^2$ value in data)
(none in over 50 million trials)

P-value from pseudo-experiments: $<2 \times 10^{-8}$; $>5\sigma$

It is difficult to model the background shape in the peak 2 range due to possible effect from possible ϕK^+ resonance. We do not quote a numeric significance for peak 2. However, there is a **clear evidence for a second structure**.

Robustness Checks

- ✿ All main requirements are varied step by step to investigate possible bias
- ✿ Each sideband-subtracted Δm distribution is compared to the default one
- ✿ No indication of a bias
one example with tighter cuts and purer B sample is shown below:
(tighter lifetime cut, tighter ϕ mass window)



◆ B purity $\sim 60\%$ within $\pm 1.5\sigma$ of $m(B^+)$

◆ similar Δm spectrum

Systematic Uncertainties

	m_1 (MeV)	Γ_1 (MeV)	m_2 (MeV)	Γ_2 (MeV)
B ⁺ background PDF	0.8	7.4	2.6	9.9
B ⁺ signal PDF	0.2	3.6	2.7	0.2
Relative efficiency	4.8	6.0	0.9	10.0
Δm binning	3.7	1.5	2.7	0.2
Δm structure PDF	0.8	9.3	0.6	4.9
Δm mass resolution	0.8	6.4	0.6	4.6
Δm background shape	0.2	7.0	0.3	0.2
Selection requirements	0.8	7.8	5.5	1.8
Total	6.3	19	7.3	16

*Extensive investigation of possible systematics from various sources
The table skipped other negligible items from our tests*

*The overall systematic uncertainties are found by adding in quadrature
of the individual items*

CMS Result

Y(4140):

$m_1 = 4148.0 \pm 2.4(\text{stat.}) \pm 6.3(\text{syst.}) \text{ MeV}$,

$\Gamma_1 = 28^{+15}_{-11}(\text{stat.}) \pm 19(\text{syst.}) \text{ MeV}$

Significance: $>5\sigma$

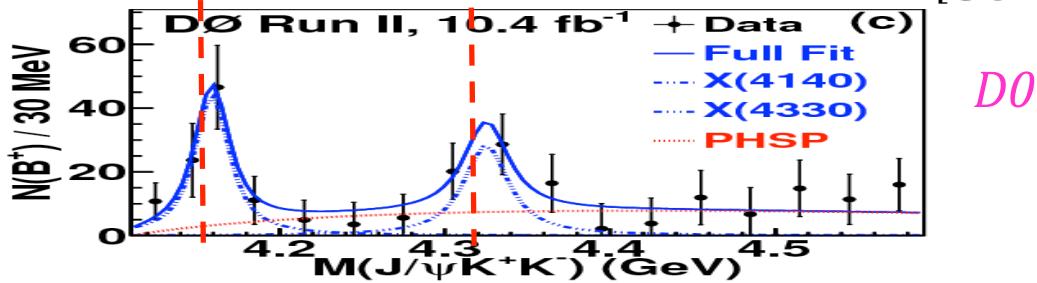
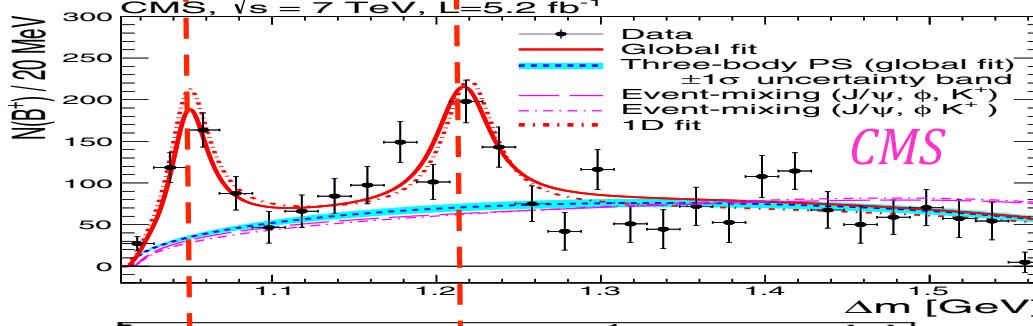
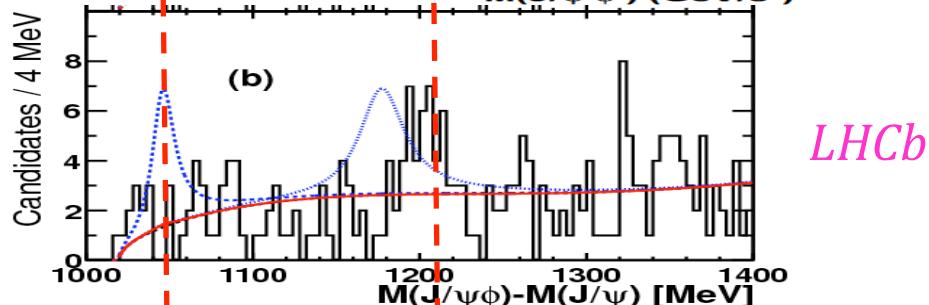
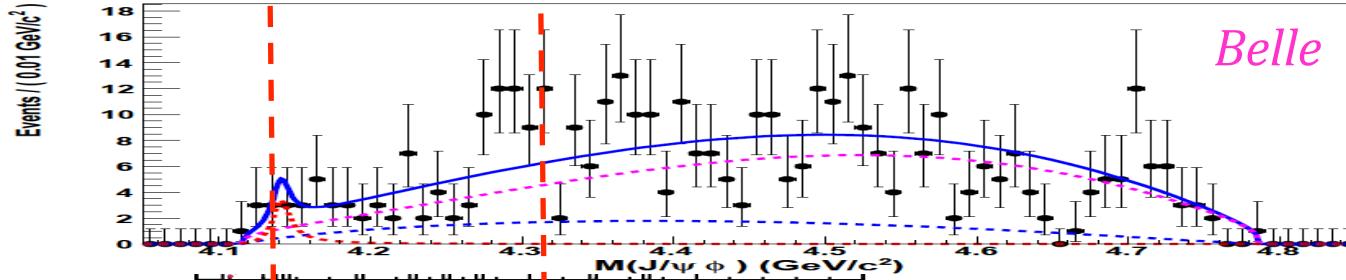
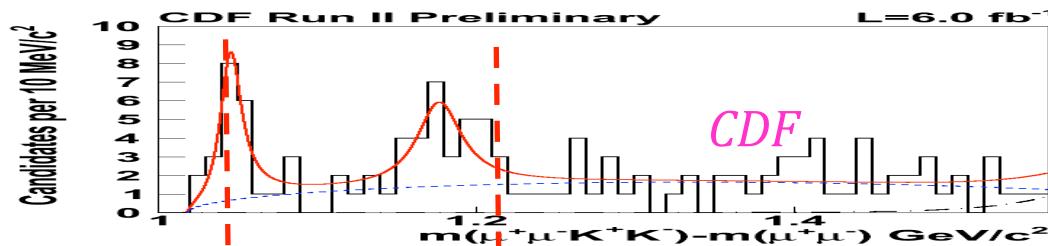
An additional peaking structure:

$m_2 = 4313.8 \pm 5.3(\text{stat.}) \pm 7.3(\text{syst.}) \text{ MeV}$,

$\Gamma_2 = 38^{+30}_{-15}(\text{stat.}) \pm 16(\text{syst.}) \text{ MeV}$

Significance: $>3\sigma$

- ▶ Observed a J/ $\psi\phi$ structure at 4148MeV with a significance greater than 5σ confirms the existence of Y(4140) from CDF (& D0 from previous speaker):
CDF Y(4140): $m=4143.4^{+2.9}_{-3.0}(\text{stat}) \pm 0.6(\text{syst})$, $\Gamma=15.3^{+10.4}_{-6.1}(\text{stat}) \pm 2.5(\text{syst}) \text{ MeV}$
- ▶ Evidence for a second structure at $\sim 4314 \text{ MeV}$ in the same mass spectrum



*Belle & LHCb miss peak 1
(low efficiency & low statistics)*

*All experiments show activities
around 4.3 GeV range, but mass
are not aligned well*

Experimental Status

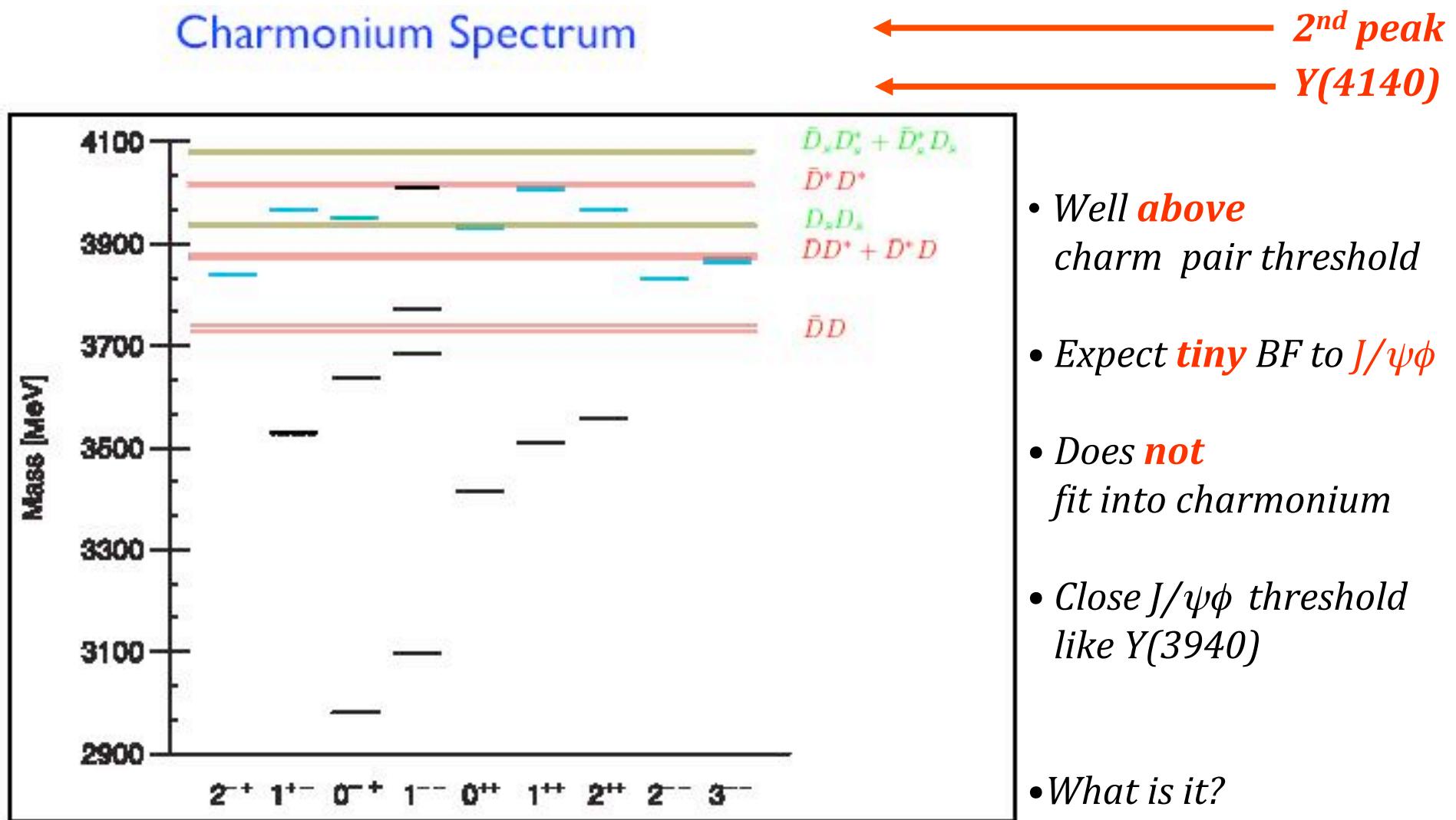
Y(4140) is experimentally established! Precise parameter measurement and J^{PC} ?

experiment	m(MeV)	Γ (MeV)	% of $B^+ \rightarrow J/\Psi \phi K^+$	Significance
CDF	4143.4 ± 3.1	15.3 ± 10.7	0.15 ± 0.05	5σ
CMS	4148.0 ± 6.7	28 ± 24	~ 0.1	$>5\sigma$
D0	4159.0 ± 7.9	19.9 ± 14.9	0.21 ± 0.09	3.1σ
Belle			$<0.12 @ 90\%$	1.9σ
LHCb			$<0.07 @ 90\% CL$	2.4σ tension

More experimental work is needed to clarify the second peak around 4.3 GeV

experiment	m(MeV)	Γ (MeV)	% of $B^+ \rightarrow J/\Psi \phi K^+$	Significance
CDF	4274.4 ± 8.6	32.3 ± 23.2		3.1σ
CMS	4313.8 ± 9.0	38 ± 34		$>3\sigma$
D0	4328.5 ± 12.0			$<3\sigma$
LHCb			$<0.08 @ 90\% CL$	

What is it?



Possible Interpretation of the $Y(4140)$

Conventional charmonium—not likely. High mass, relative narrow width

$D_s^{+}D_s^{*-}$ molecule—80 MeV above $Y(4140)$ mass, binding by meson exchange
no further confirmation for its expected decay $D_s^{*+}D_s^{*}\gamma$.
Belle's two photon width disfavor molecule with $J^{PC}=0^{++}, 2^{++}$*

$c\bar{c}q\bar{q}$ tetra-quark—tetra-quark state w/o substructure, predicted with ~ 100 MeV, experimental width seems not support

*Charmonium hybrid—mixture of gluons with charm quark pair. Predicted width to be wide. It can be narrow if $J^{PC}=1^{-+}$ and mass lie below $D^{**}D$. D^*D is an important channel, no observation*

Hadro-charmonium—binding a compact charmonium state inside an excited state of light hadronic matter, QCD analog of the van der Waals force.

CUSP—non-resonance, kinematic effect.

Possible Interpretation of peak 2

Conventional charmonium—not likely. High mass, relative narrow width

Anti- $D_s^0 D_s^0(2317)$ molecule—similar arguments as $Y(4140)$ as molecule

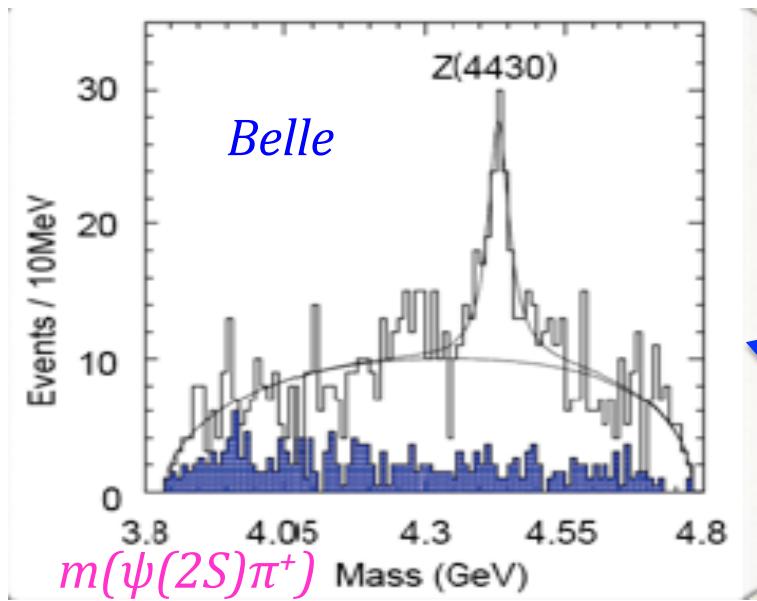
Charmonium hybrid—in the predicted hybrid mass region as $Y(4140)$

Hadro-charmonium—Multiple states with $Y(4140)$

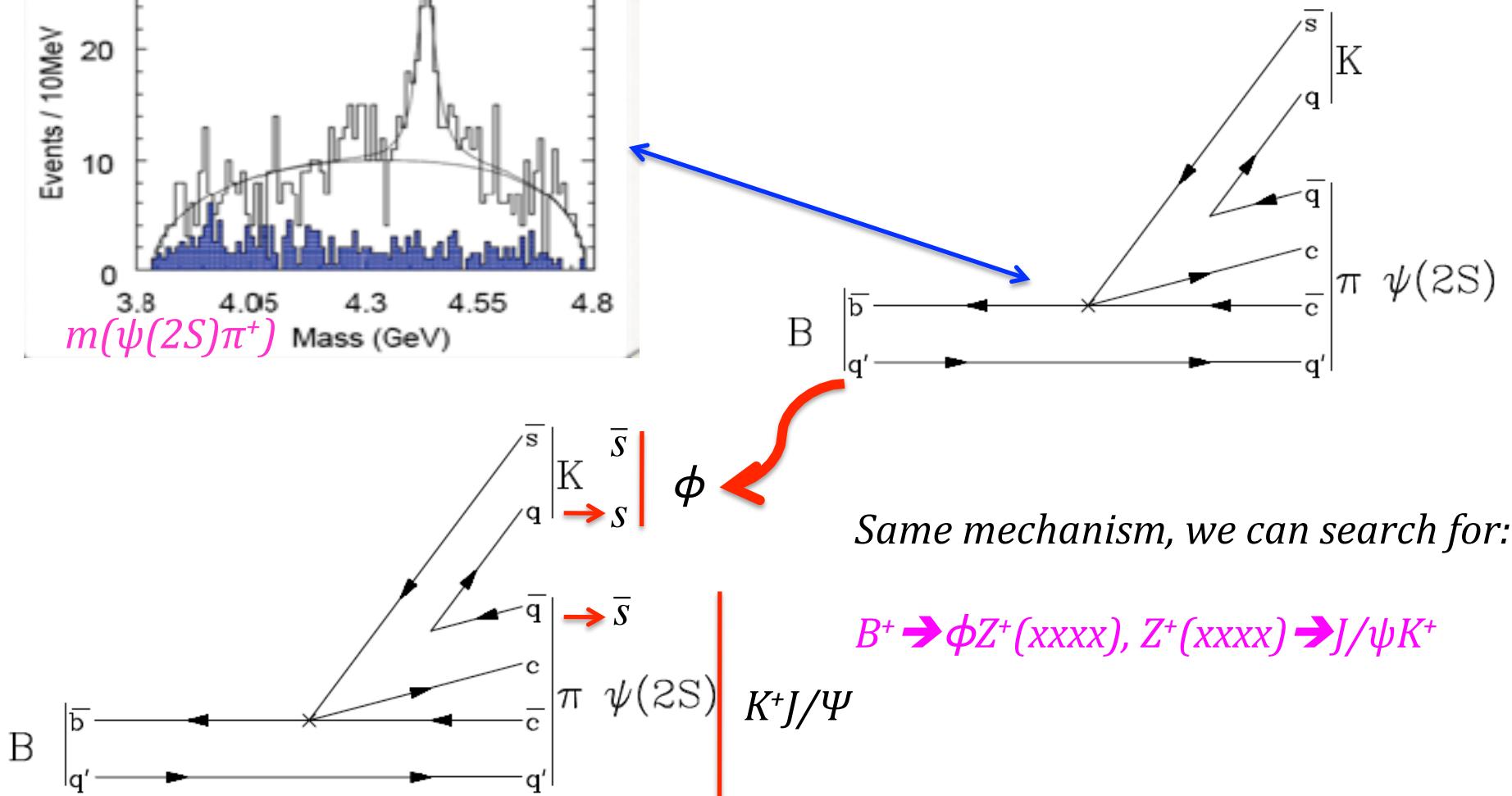
?

More statistics needed to clarify it; and more precise determination of parameters needed; detailed understanding of relevant channels such as $J/\psi\omega$ etc.

Search Possible Charged Exotics in $J/\Psi K^+$ Spectrum



arXiv: 0708.3496 [hep-ph], Jonathan Rosner
 Mechanism to produce $Z^+(4430)$:
 $B \rightarrow K Z^+(4430), Z^+(4430) \rightarrow \psi(2S)\pi^+$



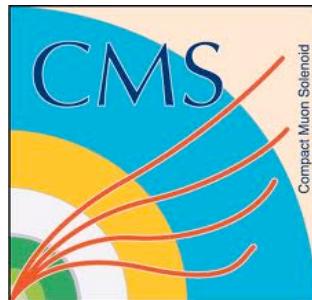
Same mechanism, we can search for:

$B^+ \rightarrow \phi Z^+(xxxx), Z^+(xxxx) \rightarrow J/\psi K^+$

Summary

- *$Y(4140)$ shows up in both $D0$ (3.1σ) and CMS ($>5\sigma$) data, parameter values are consistent with CDF result.*
 $Y(4140)$ is confirmed and established experimentally.
- *Evidence for a second structure* is found by CMS , $D0$ data can accommodate a second structure, too.
- *More to be expected with the large data sample from 2012 @LHC*

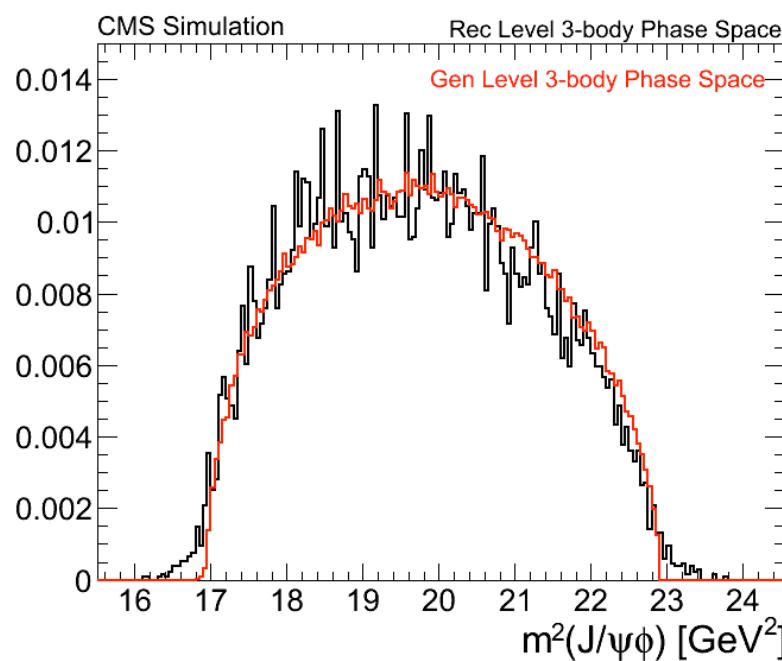
Stay tuned!



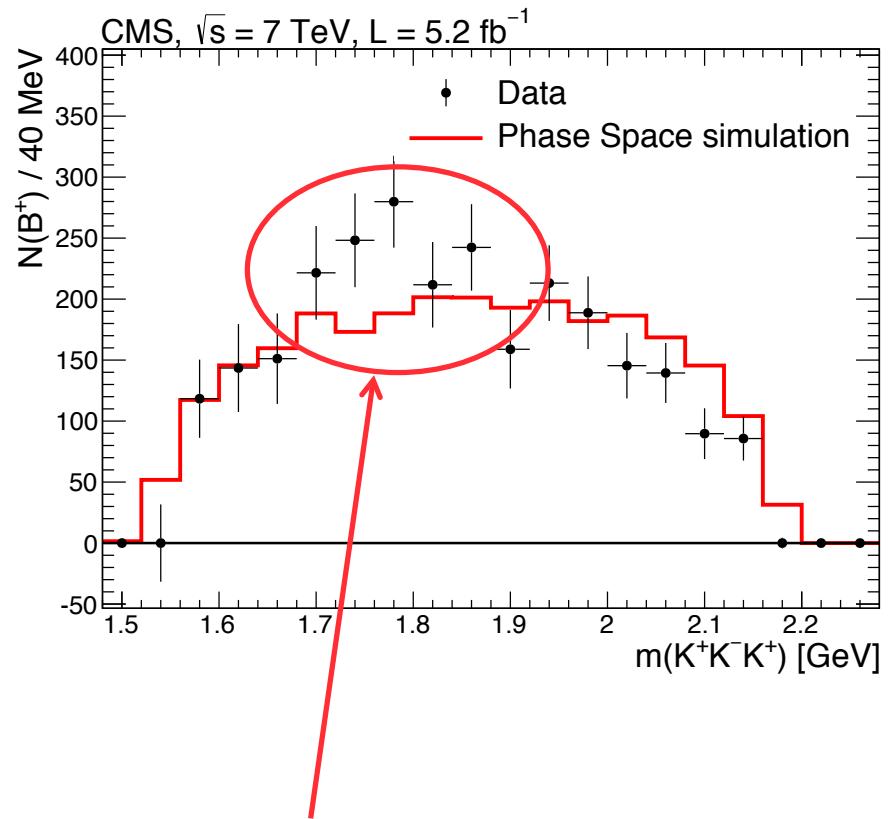
Backup

Background Shape Studies

The phase space Dalitz projection on $m^2(J/\psi\phi)$
 generated events (red)
 Vs
 reconstructed events (black)



Sideband subtracted KKK mass
 Phase Space MC (red)
 Vs
 data (black)



CMS detector does not produce peaks
 Also imply relative flat efficiency

$K_2(1770)?$
 Does it effect Δm ?

Reflection Studies

- No reported $J/\psi K^+$ resonances
- No established resonances in ϕK^+ spectrum
PDG listed possible K_2 , right plot. We investigated it further on K_2 , next slide.
- Mimic resonances in $m(J/\psi K^+)$ and $m(\phi K^+)$ for various angular distributions, failed to produce the pattern observed in the data
- Ignore possible interference, expect to affect lineshape, but not big signal
- A full amplitude analysis is desirable, limited by statistics and high combinatorial background

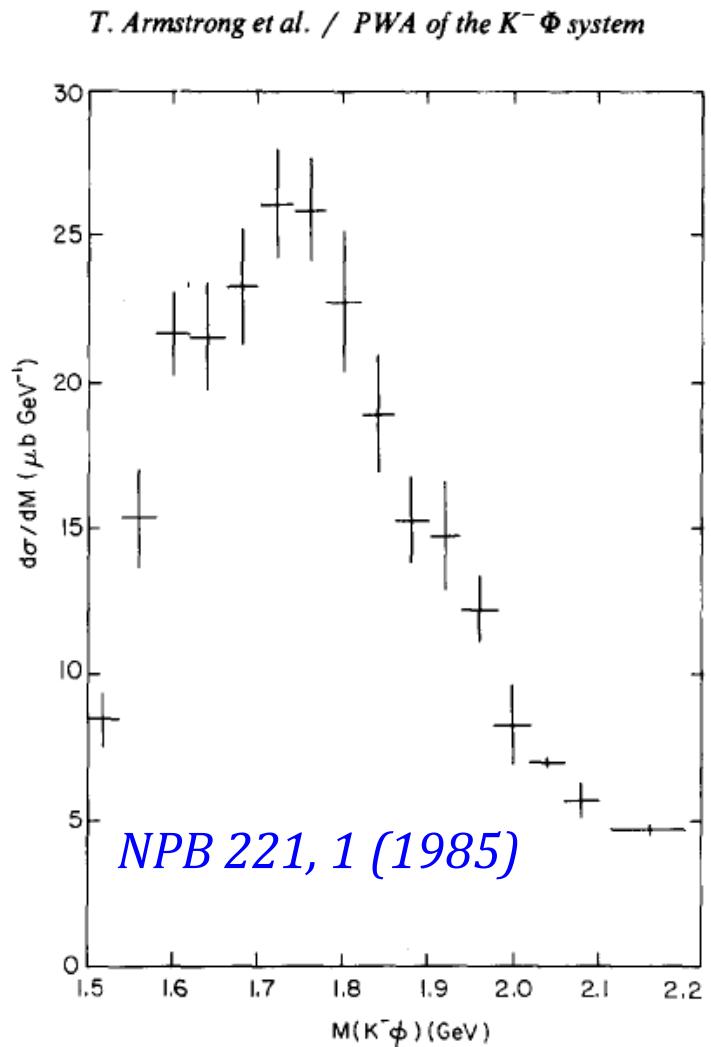
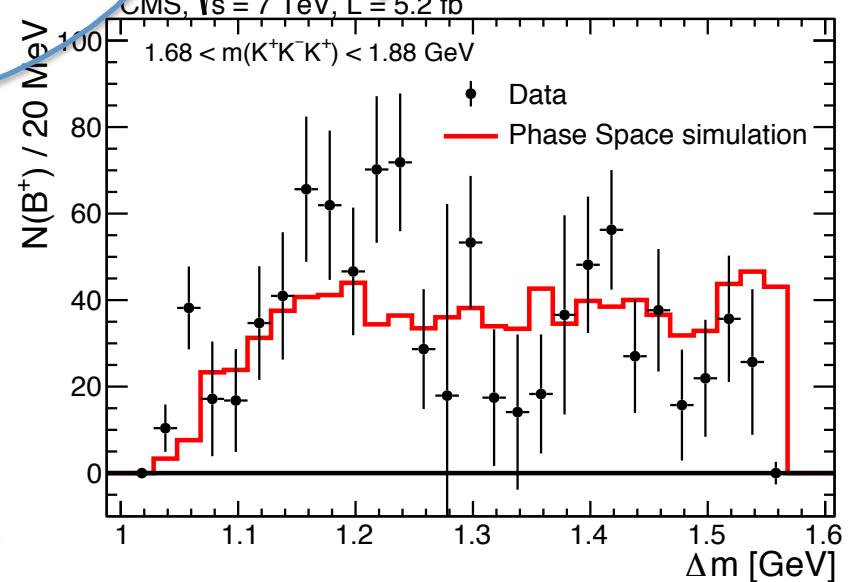
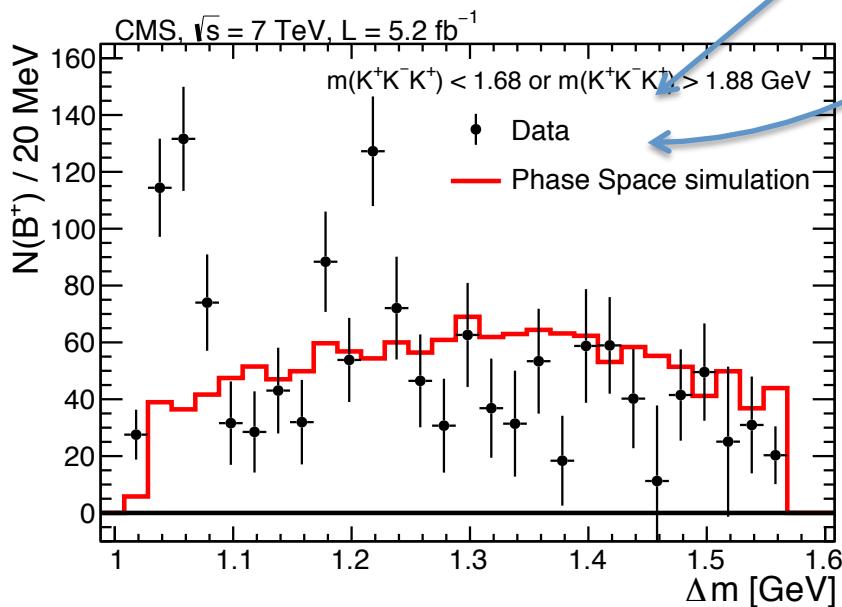
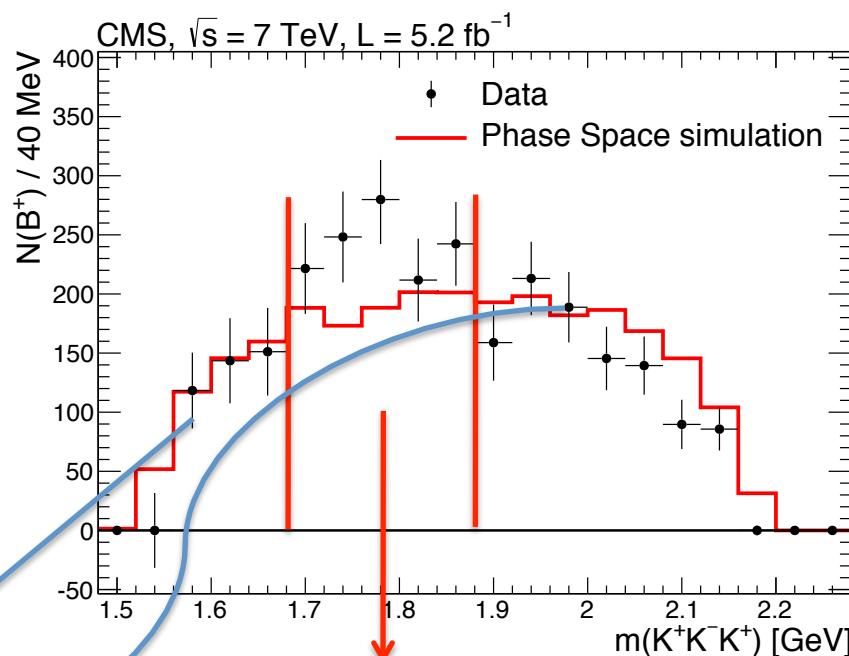


Fig. 7. Corrected $K^- \Phi$ mass spectrum for $t' < 0.8 \text{ GeV}^2$.

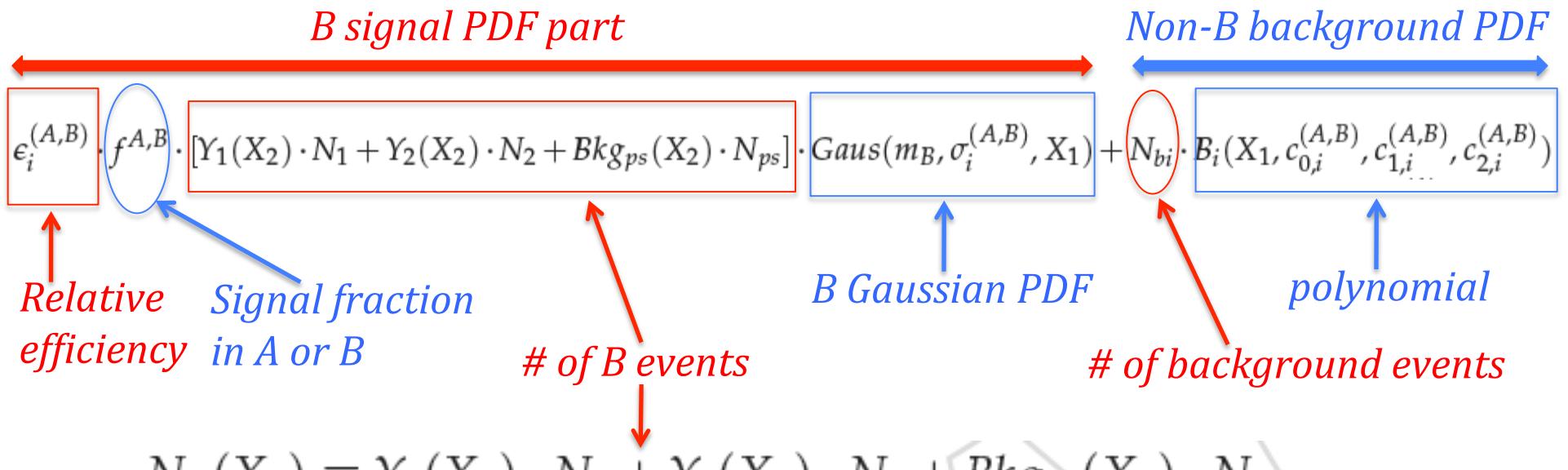
Possible ϕK^+ Resonances Studies

- The Y(4140) is still apparent after excluding the K_2 region
- Peak 2 is reduced but still visible
- Possible K_2 could distort Δm shape and affect extraction parameters, but does not affect existence



Global Fit

- Fit $m(J/\psi\phi K^+)$ (X_1) and $m(J/\psi\phi)$ (X_2 , transformed to Δm) simultaneously
Fit all Δm bin in data set A & B simultaneously
- Probability Density Function (PDF) for bin i is defined as (A&B for dataset A&B):



Y —Breit-Wigner; Bkg_{ps} —Phase space shape; N —number of events

Insert BW and PS into the fit to B mass spectrum!

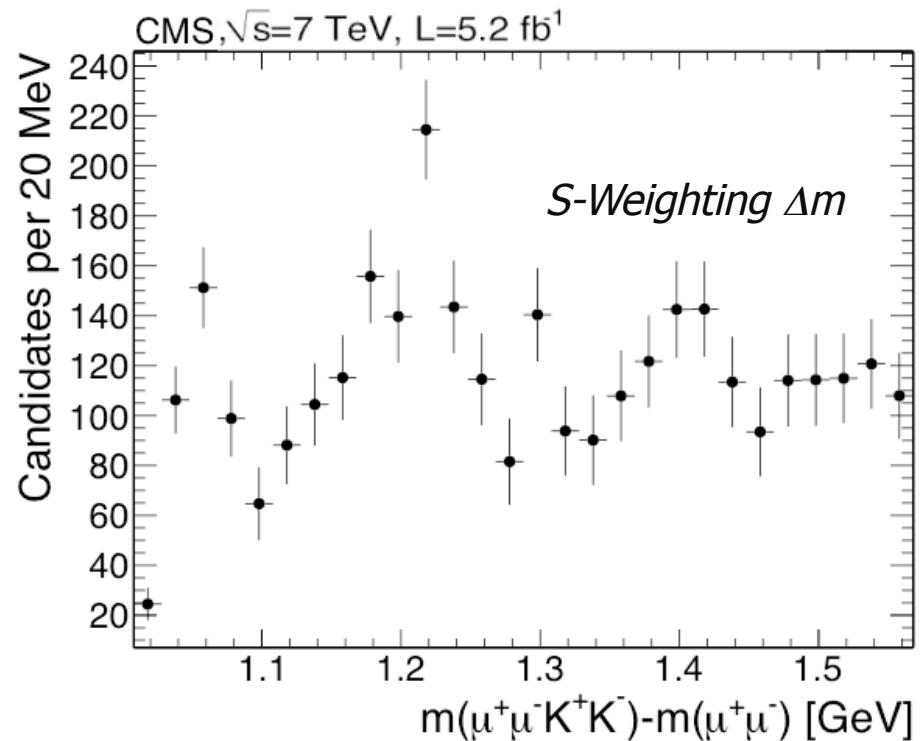
Robustness Checks

- Many checks to investigate the robustness of the two structures

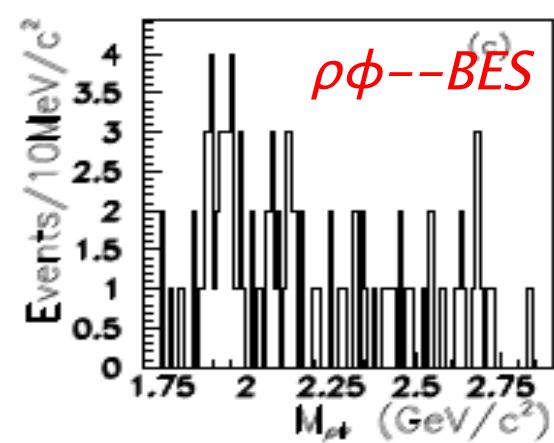
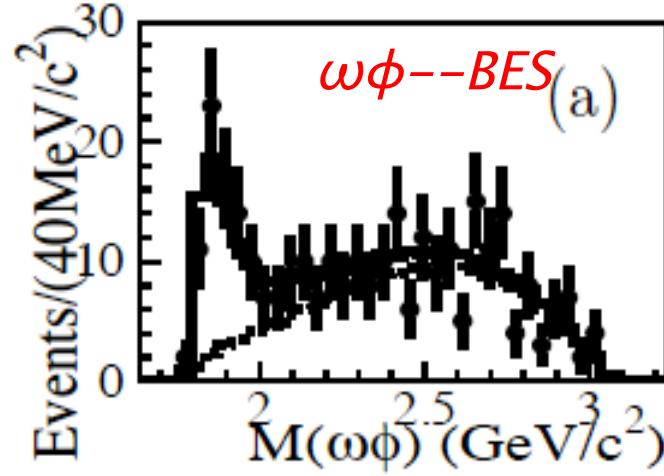
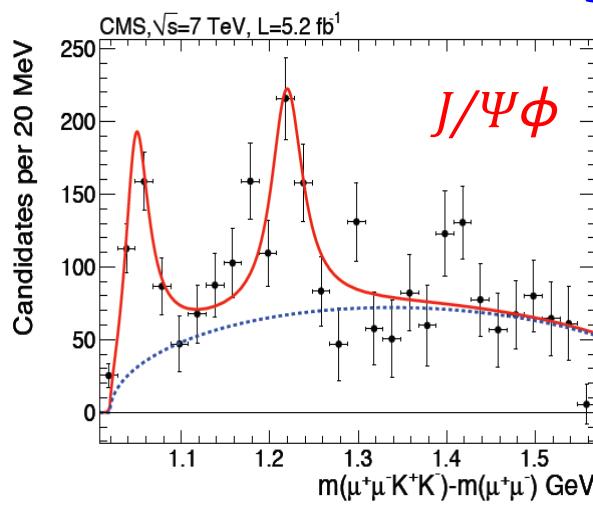
- ✿ *Variations on selection cuts,
different background and signal shapes,
different Δm binning...*

- ✿ *Different Background-subtraction
technique: sPlot*

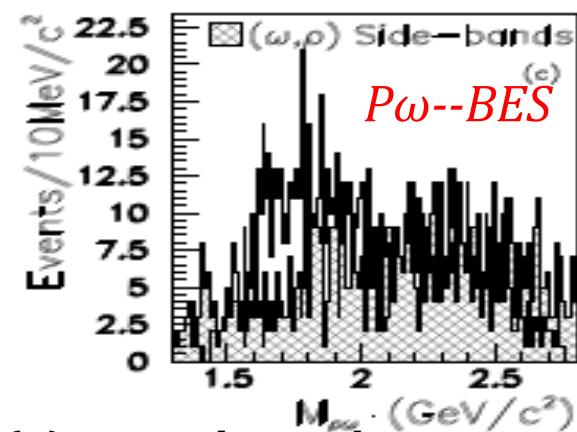
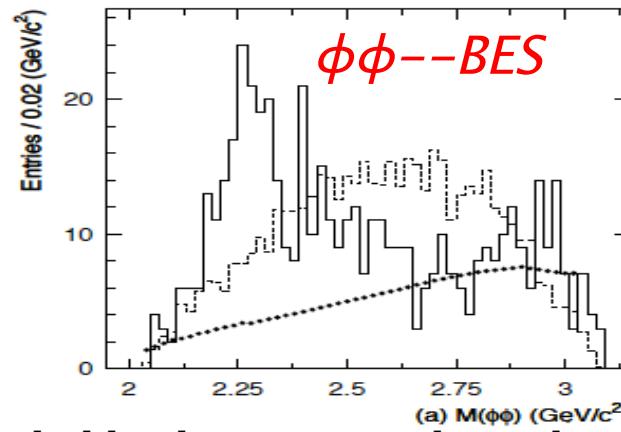
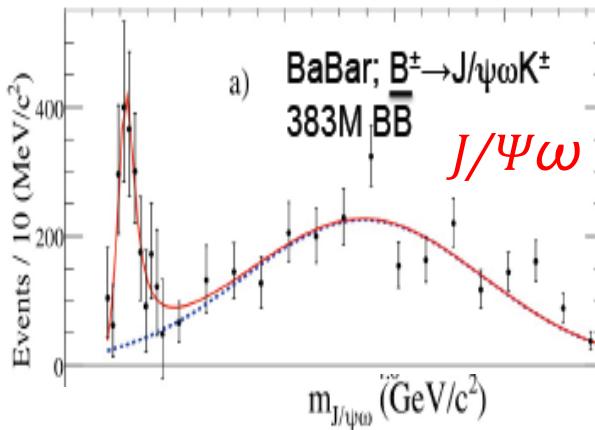
*sPlot is a technique of
background-subtraction
by weighting each event
based on observed signal to
background ratio.*



Mini Summary of near VV threshold behavior



PRD 77, 012001(2008)



$I(V,V)=0$, observed near VV threshold enhancement, through (double) OZI suppressed process

$I(V)=1$, no clear enhancement
Skip complicated $\omega\omega$, $\rho\rho$

Observed near $V(I=0)V$ ($I=0$) threshold enhancement. Strong decay. Above ($qq'+q'q$) threshold. What are they?

More on Peak 2 (@4.3 GeV)

<http://indico.ifj.edu.pl/MaKaC/materialDisplay.py?contribId=832&sessionId=19&materialId=slides&confId=11> (last page)

Five experiments show activities around 4.3 GeV

Masses are not well aligned

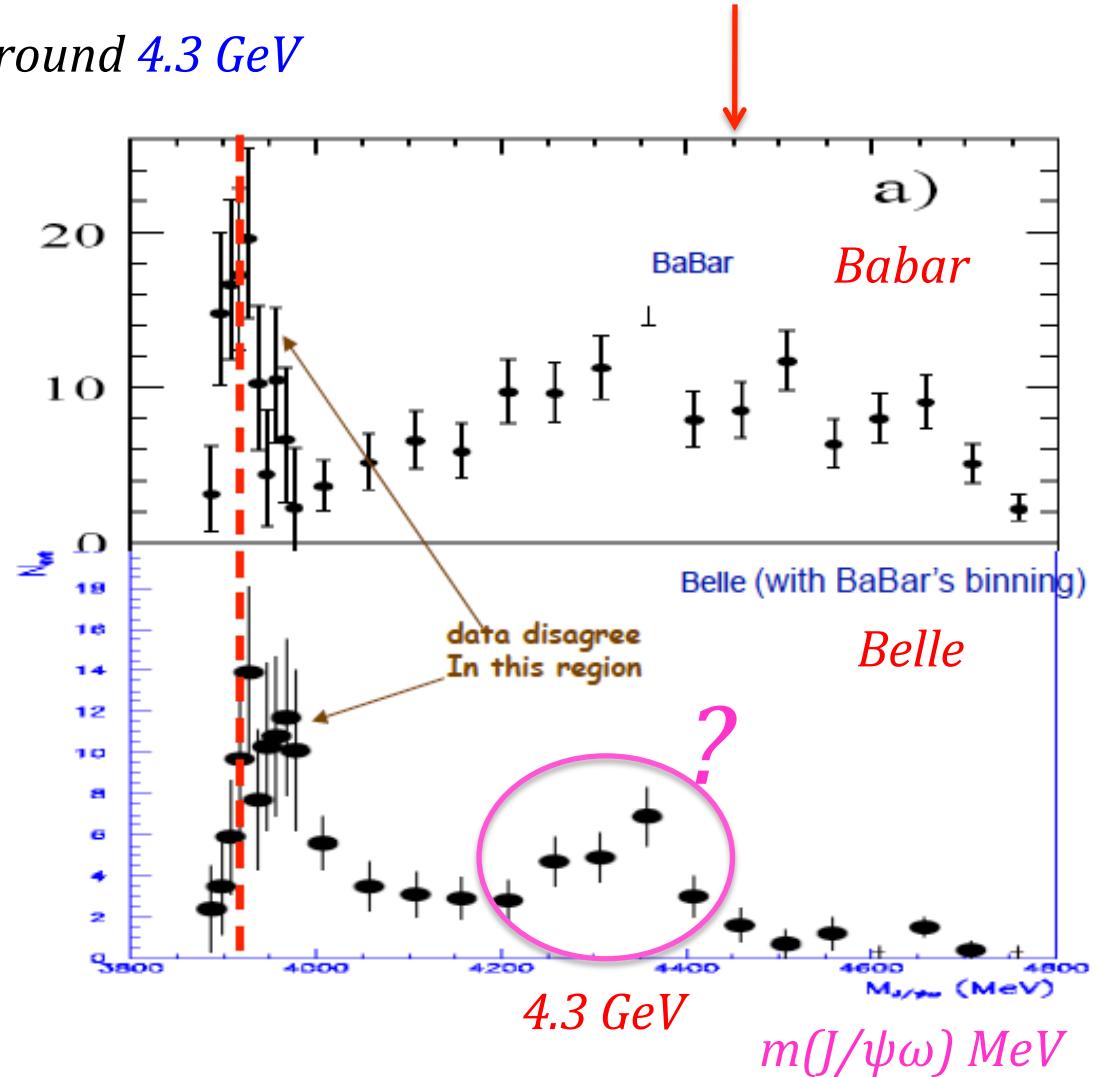
No experiment reached 5sigma

*Activities around 4.3 GeV
in $m(J/\psi\omega)$ from B factories?*

*It is mysterious even though it
is not established*

More statistics is needed!

Search for $m(J/\psi\gamma)$?



The ϕ Signal

